

THE BLAST ENERGY EFFICIENCY OF GAMMA-RAY BURSTS

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ABSTRACT

Using data mostly assembled by previous authors, we note a linear correlation for 17 of 22 gamma-ray bursts (GRBs) between the apparent radiative efficiency ϵ_γ (defined as the ratio of isotropic equivalent radiative output to inferred isotropic equivalent kinetic energy of the blast) and E_{peak}^α , where, for linearity, the exponent α is empirically determined to be in the range $1.4 < \alpha < 2$. This is consistent with the hypothesis that ϵ_γ and E_{peak} are influenced by viewing angle. We suggest a more general theoretically derived expression for this correlation that could be tested with a richer data set. If the reduction in both ϵ_γ and E_{peak} is due to viewing angle effects, then the actual radiative efficiency is ~ 7 . We also find preliminary evidence (with the remaining small sample of five GRBs) for a separate class of weak GRB afterglows.

Subject heading: gamma rays: bursts

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1. INTRODUCTION

It is well understood that the highly super-Eddington luminosities associated with GRBs are liable to put most of their energy into a baryonic wind if the energy release is in a position to drag matter outward. One solution for this (Mészáros & Rees 1994) is that at distances $\geq 10^{14}$ cm from the central burster, internal shocks in a baryonic outflow release some fraction of the bulk expansion energy by accelerating particles, which then radiate γ -rays. This probably predicts that typically 10%–50% of the energy could be recovered and put back into radiation. It also predicts that the γ -rays are always accompanied by baryonic outflow along the same direction to within $1/\Gamma$.

Alternatively, it may be supposed that the energy release is originally devoid of baryons (e.g., if the energy emerged along event horizon–threading field lines; Levinson & Eichler 1993) and that the baryon content of the GRB fireball is whatever it subsequently swept up, either from the sides (Eichler & Levinson 1999; Levinson & Eichler 2003) or from the ambient material into which the fireball expands (e.g., Mészáros & Rees 1992; Lyutikov et al. 2004). If the fireball were able to sweep up ambient material without originally having any baryons, then an afterglow would be “guaranteed,” provided that the ambient medium had sufficient density. However, if the asymptotic Lorentz factor Γ_a of the fireball were too large, then it would not pick up ambient matter; early baryon loading or an initial baryon content, which keeps Γ_a from getting too large, is probably necessary for the GRB to have an afterglow. Moreover, the Poynting flux may be considerably less than the γ -ray flux from the central object, and baryon loading from the side downstream of such a fireball’s point of origin could reclaim some of the γ -ray energy for generating afterglow if its optical depth exceeded unity. The case can thus be made that baryon loading from the sides of such a fireball, as it exits baryon-rich surroundings, could enhance the blast efficiency until it is of order unity. (In this paper, the blast efficiency, ϵ_k , refers to the isotropic equivalent kinetic energy, E_k , divided by the isotropic equivalent γ -ray energy output, $E_{\gamma, \text{iso}}$. The γ -ray efficiency, ϵ_γ ,

refers to the inverse of the blast efficiency, and either quantity can be greater than unity.)

There is no guarantee that early baryon loading from the sides penetrates the entire fireball; there exists the logical possibility that one could have a γ -ray–bright GRB with little or very weak afterglow. Previous estimates (Levinson & Eichler 2003; Eichler & Levinson 2004, hereafter EL04) suggested a picture in which the penetration is only $\frac{1}{3}$ – $\frac{1}{2}$ of the angular distance to the center from the outside, depending on the duration. Longer bursts may allow greater penetration, but this remains to be checked observationally. Observers close to the axis of symmetry might therefore see afterglow only if the spread in the afterglow beam, which is smeared by an additional $1/\Gamma(t)$ [where $\Gamma(t)$ is the Lorentz factor of the blast at observer time t] beyond the angle into which the baryons have penetrated, covers their line of sight. Typical numbers might be a beam opening angle of 0.1 rad and a penetration angle of 0.03–0.04 rad, corresponding to $1/\Gamma_{\text{fs}}$ (where Γ_{fs} is the Lorentz factor of the penetrating baryons; Levinson & Eichler 2003), and $1/\Gamma(t)$ for typical afterglow observation times of ~ 10 hr is about $1/30$ – $1/10$. Although this is about enough to cover the entire range of viewing angles over which the GRB would be seen (Eichler 2005), it is just barely so. Given the scatter in parameters so natural to astrophysical systems, we might expect to see, every now and then, a baryon-underloaded GRB with little or very weak afterglow. Such GRBs might prove very revealing.

In this paper we discuss whether the observations of several dozen afterglows are consistent with the hypothesis that some afterglows have far less afterglow efficiency than the do the majority. We find that they are; there are four or five obvious outliers relative to an otherwise expected distribution of afterglow efficiencies clustering “near” unity (but see below). It cannot of course be proved that the observed poor afterglow efficiency is due to baryon underloading. It may be due to a lower ambient density (e.g., Fan et al. 2004 and references therein) that has the effect of spreading the afterglow over a longer timescale, thus lowering the afterglow luminosity. However, this could be resolved with sufficiently thorough observations and a sufficiently large database.

In order to minimize the likelihood of indirect correlations, we first recall that afterglow efficiency is correlated with the location of spectral peak E_{peak} (Lloyd-Ronning & Zhang 2004, hereafter LRZ04). Softer GRBs seem to have lower blast efficiencies; the efficiencies scale roughly as E_{peak}^α with $1.4 < \alpha < 2$ (see below). This and its possible physical interpretations are discussed in § 2. We then plot the afterglow efficiency corrected for this correlation against burst duration and show (1) that the data appear better organized after the correction, (2) that the majority of GRBs have inferred blast efficiencies of roughly $\frac{1}{7}$, which could possibly be identified with baryon saturation, given the uncertainties, and (3) that there is no conclusive correlation with burst duration, with the present sample. We also note that several GRBs are outliers to this correlation and that all of them have anomalously *high* values for ϵ_γ .

It is emphasized that the results are not meant to be convincing beyond reasonable doubt. They are meant to show trends that we suggest should be checked with the much richer data set that *Swift* should provide. The significance of the trends, if real, would be some or all of the following implications: (1) Most GRBs have blast energies that are at least somewhat lower than the γ -ray energies. Previous estimates may have been influenced by the preferential underrepresentation of the γ -ray energies, relative to afterglow energies, by off-beam observers. (2) While most GRBs in the data set cluster around a value of ϵ_γ of the order of a few, several have extremely large values of ϵ_γ . These could plausibly be interpreted as baryon-underloaded GRBs. According to Freedman & Waxman (2001), the blast energy estimate is independent of ambient density and they cannot be interpreted as GRBs that took place in an underdense environment if the observed X-ray frequency is above the cooling frequency, although it can be posited that the ambient density and/or magnetic field energy was anomalously low and that the cooling frequency was anomalously high. (3) There is some indication that some of the anomalous GRBs with very high ϵ_γ tend to be short and could thus be attributed to a qualitatively different type of phenomenon and/or environment. The search for afterglow from short GRBs that can be undertaken with *Swift* will thus be important. However, three of the five lasted longer than 25 s and have no apparent distinguishing characteristics other than a weak afterglow. (4) Various explanations for the Amati et al. correlation can be tested with a good enough data set.

2. AFTERGLOW CORRELATES WITH E_{peak}

The values of E_{peak} and E_{iso} correlate according to the relation $E_{\text{iso}} \propto E_{\text{peak}}^2$ (Amati et al. 2002; Atteia et al. 2004). Two possible accounts of the $E_{\text{iso}} \propto E_{\text{peak}}^2$ correlation are (1) the dirty fireball model (e.g., Dermer 1999; Qin et al. 1998), in which baryon overloading delays transparency until photons have softened to X-ray energies, and (2) off-beam viewing, in which the observed E_{peak} is lessened by kinematic effects, viz., the reduced blueshift at the observer's viewing angle relative to that seen by an observer in the beam (EL04).

In the viewing angle model for the Amati et al. relation proposed by EL04, the apparent total isotropic equivalent fluence is viewer angle dependent. It is lowered by a viewing angle offset from the closest part of the beam by angle θ , approximately as $D(\theta, \Gamma)^2$, where $D(\theta, \Gamma) \equiv 1/\Gamma(1 - \beta \cos \theta)$. This is opposed to the $D(\theta, \Gamma)^3$ dependence that would apply to a thin pencil beam because the solid angle that makes a significant contribution to what is detected by observers just outside the beam is roughly proportional to the factor $(1 - \cos \theta) \sim 1/(1 - \beta \cos \theta)$.

The apparent afterglow fluence is also reduced by off-beam viewing, but generally not as much. Freedman & Waxman (2001) noted that X-ray afterglow fluence at $t \sim 10$ hr could be used as a calorimeter for the blast energy. The Lorentz factor after 10 hr, the typical time for *BeppoSax* measurements of afterglow, Γ_X , is expected to be about a factor of 10 less (if the expansion is into a uniform medium) than the Lorentz factor at 100 s, Γ_p . (The subscript p is for “prompt,” which refers to $t \leq 100$ s.) Hence, the reduction in prompt fluence *relative* to the fluence of X-ray afterglow is given by

$$\frac{\epsilon_\gamma(\theta)}{\epsilon_\gamma(0)} = \frac{[D(\theta, \Gamma_p)/D(0, \Gamma_p)]^2}{[D(\theta, \Gamma_X)/D(0, \Gamma_X)]^2}. \quad (1)$$

By the hypothesis that E_{peak} is established by viewing angle effects,

$$\frac{E_{\text{peak}}(\theta)}{E_{\text{peak}}(0)} = \frac{D(\theta, \Gamma_p)}{D(0, \Gamma_p)}. \quad (2)$$

After using equation (2) to eliminate the viewing angle in favor of E_{peak} , equation (1) becomes

$$\begin{aligned} \frac{\epsilon_\gamma(\theta)}{\epsilon_\gamma(0)} &= \left[\frac{E_{\text{peak}}(\theta)}{E_{\text{peak}}(0)} \right]^2 \\ &\times \left\{ \left(1 - \frac{\beta_X}{\beta_p} \right) + \left(\frac{\beta_X}{\beta_p} - \beta_X \right) \left[\frac{E_{\text{peak}}(\theta)}{E_{\text{peak}}(0)} \right]^{-1} \right\}^2 (1 - \beta_X)^{-2} \end{aligned} \quad (3)$$

Over the range of viewing angles $\theta \Gamma_X \ll 1$,

$$\frac{\epsilon_\gamma(\theta)}{\epsilon_\gamma(0)} \simeq \left[\frac{E_{\text{peak}}(\theta)}{E_{\text{peak}}(0)} \right]^2. \quad (4)$$

Thus, the viewing angle explanation for the Amati et al. relation predicts that the apparent ratio of γ -ray energy to blast energy $\epsilon_\gamma \equiv E_{\gamma, \text{iso}}/E_{k, \text{iso}}$ should decrease as E_{peak}^2 decreases, as described by equation (4). The general form, as described by equation (3), is shown in Figure 1 (*right*). Weak correlation in the intrinsic E_{peak} with the opening angle (see Fig. 5) and the fact that the beam probably does not have a sharp edge could cause the correlation to deviate somewhat from equation (4); so might other indirect correlations. In addition, pole-to-equator energy transfer, a true physical effect (Kumar & Granot 2003), may play some role. In any event, we expect the qualitative correlation to survive these considerations.

3. RADIATIVE EFFICIENCY AND SPECTRAL PEAK

We have plotted in Figure 1 (*left*) γ -ray efficiency ϵ_γ against E_{peak}^2 , defining efficiency as $E_{\gamma, \text{iso}}/E_k$, where E_k is the isotropic equivalent kinetic energy of the GRB ejecta. We have used the E_k values as presented in LRZ04 based on X-ray afterglow luminosity in Berger et al. (2003). We add more data to the plot in Figure 7 of LRZ04, using the correlation between X-ray afterglow at 10 hr and blast energy to estimate E_k for GRB 980326, GRB 980329, and GRB 000214.

The efficiency of GRB 990506 has been taken from Freedman & Waxman (2001). The data for GRB 980329 have a large

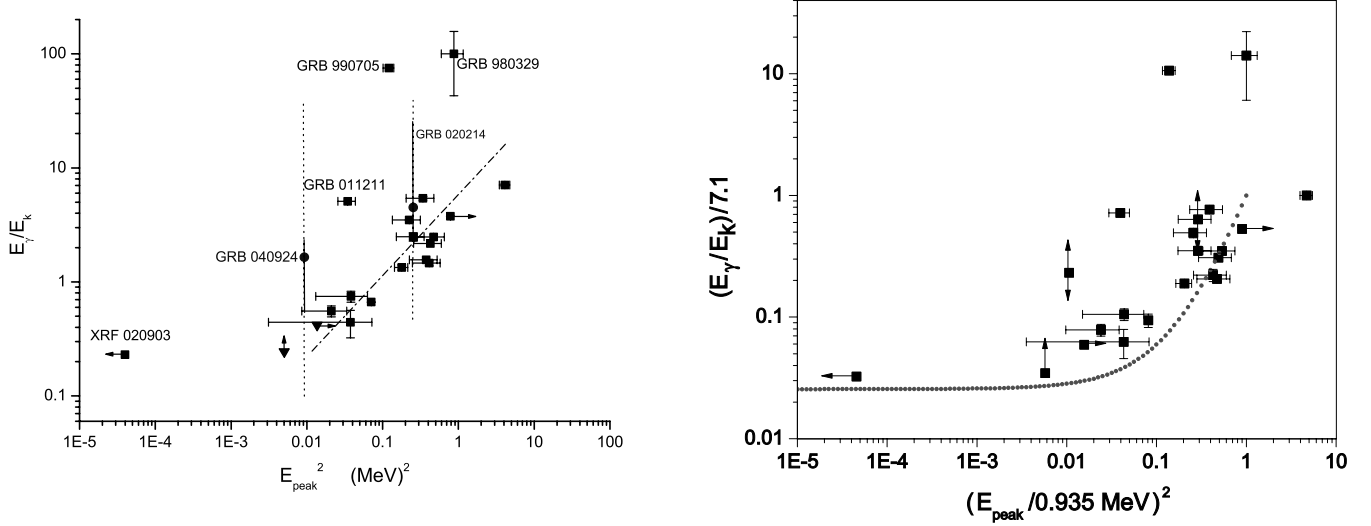


FIG. 1.—*Left*: Radiative efficiency and spectral peak. The squares show data from LRZ04, and the triangles correspond to GRB 980326 and GRB 000214. The circles correspond to the most likely efficiencies for GRB 040924 and GRB 020124, with dotted lines extending to the extremes and solid lines covering the total uncertainty for the case in which the circumburst density $n = 1 \text{ cm}^{-3}$. The dash-dotted line is described in the text. *Right*: Radiative efficiency and spectral peak compared with a model for viewing angle reduction (see eq. [3]). Note in the right panel that the y-axis has been normalized relative to a universal uncorrected radiative efficiency of 7.1. The parameters for the curve are $\Gamma_p = 100$ and $\Gamma_x = 40$. [See the electronic edition of the Journal for a color version of this figure.]

uncertainty, as the redshift is uncertain ($2 < z < 3.9$). We have used the estimates by Ghirlanda et al. for $E_{\text{peak}}(1+z)$ and $E_{\gamma,\text{iso}}$. Using equation (1) in Berger et al. (2003) and the relation between $L_{X,45}(10 \text{ hr})$ and $E_{k,52}$ of LRZ04,¹ this would give GRB 980329 an isotropic blast kinetic energy value of $E_{k,52} = 2.1 \pm 1.0$.

The radiative efficiency we calculate differs from that calculated by Freedman & Waxman (2001), who used an assumed value for the redshift for their calculations. For all GRBs, we have used values for $E_{\text{peak}}(1+z)$, T_{90} , and $E_{\gamma,\text{iso}}$ from Ghirlanda et al. (2004), Bloom et al. (2003), and the *High Energy Transient Explorer (HETE)* Web site. We also add GRB 020124, whose blast energy we estimate below. Finally, the discovery of the host galaxy of GRB 040924 has allowed the redshift to be measured at $z = 0.859$ (Wiersema et al 2004), as well as $E_{\gamma,\text{iso}}$. We have taken E_{peak} from the *HETE* Web site.² Below we estimate the kinetic energy of GRB 040924.

GRB 040924.—The afterglow of GRB 040924 is reproduced in Fan et al. (2004) and can be extrapolated for $F_{\nu,\text{max}} \geq 250 \mu\text{Jy}$, using $F_\nu = F_{\text{max}}(\nu/\nu_m)^{-(p-1)/2}$ (Sari et al. 1998). In this case $p = 2.42$ and $t_d = 1.09 \times 10^{-2}$ (Fan et al. 2004). The E_k and its uncertainty have been calculated using the equations of adiabatic afterglow evolution (Sari et al. 1998) as arranged below, with $D_{28} = 1.68$:

$$E_{k,52} = (4.03 \times 10^{-36}) \nu_m^2 \epsilon_e^{-4} \epsilon_B^{-1}, \quad (5)$$

$$E_{k,52} = (2.56 \times 10^{-5}) F_{\nu,\text{max}} \epsilon_B^{-1/2} n_0^{-1/2}. \quad (6)$$

This allows upper and lower bounds to E_k to be calculated, with reasonable ranges assumed for the unknown parameters: $[0.03, 0.3]$ for ϵ_e , $[10^{-3}, 10^{-2}]$ for ϵ_B , and $[0.01, 3] (\text{cm}^{-3})$ for n_0 .

These equations are plotted in Figure 2 to show the bounds imposed on E_k as a function of $F_{\nu,\text{max}}$. We include in this plot the

lines corresponding to equation (6) for the circumburst density $n_0 = 1$.

The most likely value for $E_{k,52}$ has been taken as the center of the polygon bounded by the equations and the line $F_{\nu,\text{max}} = 250 \mu\text{Jy}$. We add the extreme cases, as well as the limits on E_k that result from assuming $n = 1 \text{ cm}^{-3}$, for comparison with our results. We find the best value of $E_{k,52}$ to be 0.9 with extremes at $0.04 < E_{k,52} < 15$ and a range for the case $n_0 = 1$ of $0.65 < E_{k,52} < 2.75$.

GRB 020124.—By the same method employed for GRB 040924, we have used the afterglow light curve produced in Berger et al. (2002) to calculate the kinetic energy of GRB 020124 over the same ranges for the unknown parameters, using $D_{28} = 8.38$. We found that in the limits of uncertainty $0.74 < E_{k,52} < 70.5$, and for the case $n = 1 \text{ cm}^{-3}$, $1.22 < E_{k,52} < 11.61$, and the most likely blast energy is $E_{k,52} \simeq 4.51$.

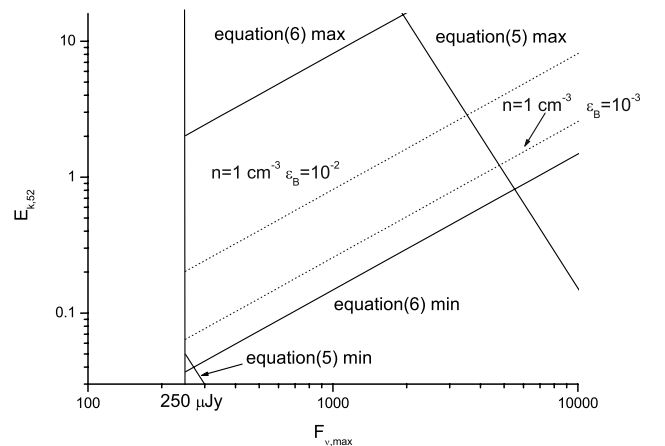


FIG. 2.—Bounds imposed on E_k from eqs. (5) and (6), for all $F_{\nu,\text{max}} \geq 250 \mu\text{Jy}$. The line labeled “equation (6) min” is a limit imposed by eq. (6) assuming $n = 3 \text{ cm}^{-3}$ and $\epsilon_B = 0.01$; E_k is excluded below this line. The lines labeled “equation (6) max,” “equation (5) min,” and “equation (5) max” show the other relevant limits as defined in the text. The dotted lines correspond to limits at which $n = 1 \text{ cm}^{-3}$ for comparison. [See the electronic edition of the Journal for a color version of this figure.]

¹ In this paper, we use the usual cgs subscript convention $Q = 10^x Q_x$.

² See <http://space.mit.edu/HETE/Bursts/GRB040924/>.

4. RESULTS

The radiative efficiency of each GRB is plotted as a function of the spectral peak. There are 17 GRBs closely correlated along the dash-dotted line of best fit, with the remaining five outliers being XRF 020903 (8.0 σ above the line), our estimate for GRB 040924 (4.2 σ), GRB 011211 (4.5 σ), GRB 990705 (7.9 σ), and GRB 980329 (5.7 σ), where the standard deviation is computed for $\log(E_\gamma/E_k)$ relative to the corresponding value given by the linear fit ($\sigma = 0.23$ for the group of 17 well-correlated GRBs). The existence of these bursts with exceptional radiative efficiency, roughly an order of magnitude above the majority for a given E_{peak} , provides evidence of a distinct subclass of GRBs. The slope of the best-fit line in this plane reveals a correlation whereby $E_\gamma/E_k \sim E_{\text{peak}}^{1.5}$. The Pearson correlation coefficient without the five outliers is 0.72 and with the five outliers is 0.10.

Radiative efficiency, spectral peak, and T_{90} .—We include a graph (Fig. 3) of γ -ray efficiency corrected for the correlation noted above, as a function of T_{90} , taking T_{90} from Ghirlanda et al. (2004) or the *HETE* Web site.

In this plane, there appears to be a general population of GRBs whose value of $E_\gamma/(E_k E_{\text{peak}}^{1.5})$ clusters near a value of about 7, all to within a factor of 2, except for five outliers. Contrast this with Figure 4, where the naive efficiency (i.e., uncorrected for $E_{\text{peak}}^{1.5}$) has either a larger scatter or some dependence on T_{90} . The correlation in Figure 4 with the uncorrected efficiency has a correlation coefficient of 0.54, whereas the correlation disappears for the corrected efficiency (in each case these correlation coefficients are without the five outliers). This suggests a universal value for blast efficiency corrected for viewing angle effects, whereas *not* making this correction would leave much larger scatter in the blast efficiency. The outliers XRF 020903 and GRB 040924 are rather short bursts although still at least ~ 1 s. However, GRB 990705, GRB 980329, and GRB 011211 all lasted at least 25 s.

Viewing angle calculations and radiative efficiency.—If we can assume that viewing angle on the jet is the *only* factor that reduces an otherwise standard radiative efficiency and standard spectral peak of GRBs, then we can compare equation (3) with

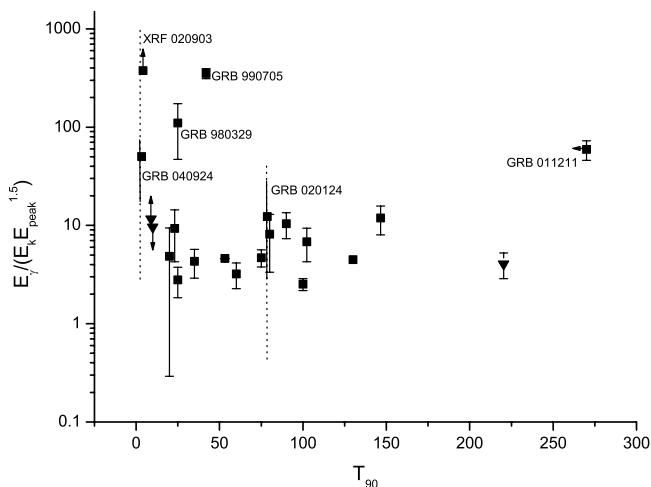


FIG. 3.—Radiative efficiency over spectral peak, corrected for the $E_{\text{peak}}^{1.5}$ correlation, plotted against T_{90} . The triangles show GRB 980326, GRB 990506, and GRB 000214. For the uncertain cases of GRB 040924 and GRB 020124, the dotted lines extend to the possible extremes, and the solid lines cover the range for the case in which $n = 1.0 \text{ cm}^{-3}$.

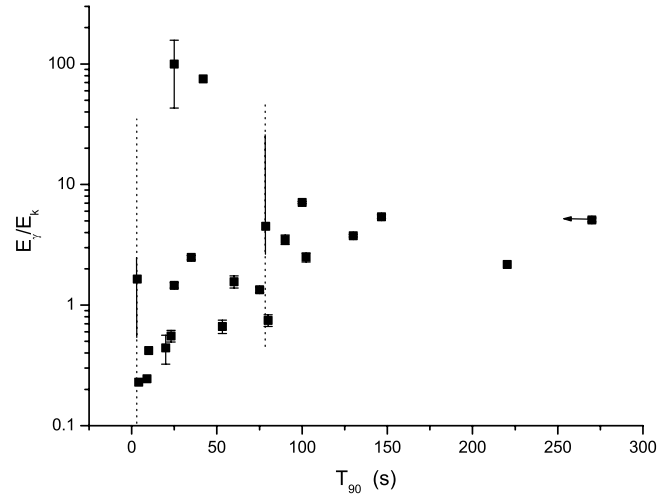


FIG. 4.—Radiative efficiency, uncorrected for the E_{peak} correlation, plotted against T_{90} .

the plot we have made in Figure 1, normalizing both the efficiency and E_{peak} to be unity for observers where $\theta = 0$.

5. DISCUSSION

The question of whether short bursts have afterglows is a long-standing one. If they result from neutron star coalescence (Goodman 1986; Paczyński 1986, 1990; Eichler et al. 1989), then they might take place in regions of low ambient density (Fan et al. 2004 and references therein), which would weaken and prolong their afterglow. Here we have called attention to several weak afterglows whose GRBs were not so short, such as GRB 011211, GRB 990705, and GRB 980329. We know of no a priori particular reason for them to have had weak afterglows and suggest that they may have been the occasional bursts that we view along baryon-poor lines of sight.

With mounting evidence that GRBs may be divided into subclasses, which sheds light on jet structure or the cause of GRBs (see Bloom et al. 2003), our hypothesis would add yet another distinction between populations of GRBs. Relying on previous work, we find that for the GRBs with available data, 5 of 22 appear unassociated with what is otherwise a closely clustered population in blast efficiencies. All of them have a weak afterglow (high radiative efficiency), whereas none were particularly deviant in the opposite direction. We have speculated on possible trends in this small sample but stress our anticipation of future data.

The majority of burst efficiencies follow $E_\gamma/E_k \sim E_{\text{peak}}^{1.5}$. Ghirlanda et al. (2004) find a correlation between collimation-corrected E_γ and E_{peak} whereby $E_\gamma \sim E_{\text{peak}}^{1.4}$. The slightly shallower than E_{peak}^2 dependence found by Ghirlanda et al. can be understood if the inferred opening angle is larger for lower E_{peak} . From Figure 5 it appears that this is the case. Levinson & Eichler (2005) have recently suggested that the inferred opening angle, whose value decreases weakly with E_{iso} for a given observed break time, is biased toward larger values at lower E_{peak} because the true E_{iso} is biased toward lower values by viewing angle effects. Although a true physical anticorrelation between opening angle and E_{peak} cannot be excluded a priori, the argument of Levinson & Eichler (2005) quantitatively accounts for the difference between the Amati et al. and Ghirlanda et al. correlations. (There may be additional causes for scatter in E_{peak} , such as a dirty fireball effect, which would lower both E_{peak} and E_γ

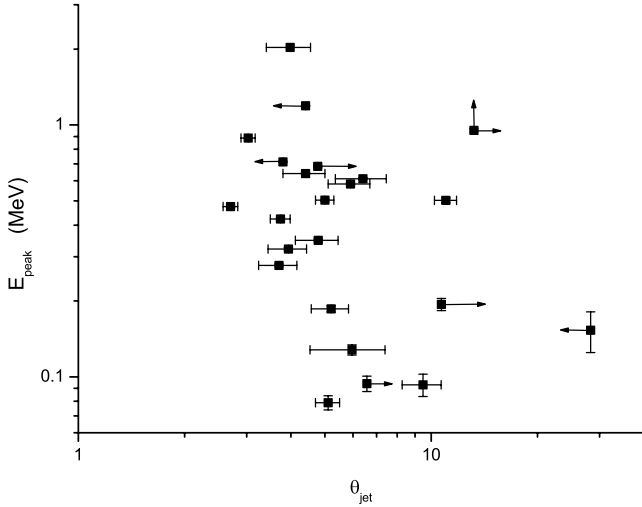


FIG. 5.—Spectral peak and jet opening angle. The data are from Ghirlanda et al. (2004). Although the correlation is not strong, there is nonetheless a slight indication that wider jets have lower spectral peaks.

but not E_k . However, it would do so at the cost of imposing an extremely small radiative efficiency.) Curiously, we find that the γ -ray efficiency has nearly the same dependence on E_{peak} as does E_γ in the correlation noted by Ghirlanda et al. This could be attributed to the simple fact that apparent γ -ray luminosity depends more on viewing angle than does apparent afterglow luminosity.

It is anticipated that *Swift* data will reveal whether there are more GRBs that are distinct from the majority by their high radiative efficiency. The sample we have used is not free of all bias; on the other hand, the sample of available redshifts may itself suffer a possible selection bias against weak afterglows, so the eventual fraction of weak afterglow GRBs may be considerably different from the 5 of 22 portrayed here.

The significance of this result, if valid, is that the blast energy as a fraction of the total energy is only about $\frac{1}{7}$ and that instances for which it is greater can be largely attributed to viewing angle-dependent reduction of the apparent radiative efficiency. Theoretical estimates for the dissipation efficiency of the internal shocks vary (Kumar 1999; Guetta et al. 2001; Beloborodov 2000; Kobayashi & Sari 2001), but in principle this efficiency could be large. Given the uncertainties and possible systematic errors, both in afterglow observations and in the theory, the value of 7 for the ratio of isotropic equivalent γ -ray energy to isotropic equivalent kinetic energy could be interpreted as a not implausible value for a baryon-saturated outflow. However, it may be uncomfortably large for the scenario in which internal shocks in a baryonic outflow convert kinetic energy to γ -ray energy, particularly because it is so tightly clustered around 7.

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